High Current Lanthanum Hexaboride Hollow Cathode for 20-200 kW Hall Thrusters

IEPC-2017-303

Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017

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Abstract: The demand for higher power Hall and ion thrusters continues for providing high thrust and long life for deep space mission. The X3 nested Hall thruster is capable of power levels in the 20 to 200-kW range, and is being developed by the University of Michigan and Aerojet for future cargo and manned-missions. The cathode for this thruster is required to produce discharge currents of 50 to 350 A with lifetimes in excess of 10 khrs. A high-current lanthanum hexaboride (LaB_6) hollow cathode was previously developed at JPL for these applications, and was successfully operated at over 250 A of discharge current. An updated version of this cathode has been designed, built and tested at JPL, and then used to run the X3 nested Hall thruster at currents of up to 250 A. The new version is designed to reduced orifice plate overheating at high currents, and is capable of injecting auxiliary gas directly into the near-cathode plume from two locations to minimize energetic ion generation at high current. The cathode is predicted to be capable of producing over 350 A of discharge current, and has been tested to date at JPL at steady-state discharge currents from 25 A to 300 A.

I. Introduction

There is continued interest in NASA for using electric propulsion thrusters to reduce launch vehicle size and provide in-space transportation of large masses for future cargo and manned-missions. The next generation Hall thrusters being developed for these high-power applications in the range of 20 to 200-kW will require hollow cathodes to produce discharge currents of 25 to over 350 A with lifetimes in excess of 10 khrs. NASA and the commercial aerospace industry in the US have spent many years developing and ultimately flying barium-oxide impregnated dispenser cathodes in various ion thrusters, Hall thrusters, plasma contactors, and plasma neutralizers at discharge currents under 25 A. These cathodes use a porous tungsten insert that is impregnated with an emissive mix of barium and calcium oxides and alumina[3,4] in a configuration called a dispenser cathode because the tungsten matrix acts as a reservoir for the barium that diffuses from the pores to evolve a barium oxide dipole on the tungsten surface that reduces the work function. Because chemistry is involved in the formation of the low work function surface, dispenser cathodes are subject to poisoning that can significantly increase the work function[8]. Care must be taken in handling the inserts and in the vacuum conditions used during operation and storage of these cathodes to avoid poisoning by water vapor and impurities in the gas that can shorten the lifetime or even prevent cathode emission. This has resulted in the requirement for high feed gas purity and extensive spacecraft feed system and propellant tank

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cleaning techniques. Finally, increasing the discharge current capability of BaO-W dispenser hollow cathodes to over 50-to-100 A typically results in overheating of the insert and reduced life.

An alternative electron emission material with a vast amount of use in both space and on the ground is lanthanum hexaboride (LaB_6). Several hundred Russian Hall thrusters have been flown over the last 40 years with LaB_6 cathodes on Russian[10,11] and Space Systems Loral communication satellites for station keeping[12,13]. LaB_6 electron emitters are also used extensively in university research devices and many industrial applications such as plasma sources, ion sources, arc melters, optical coaters, ion-platers, scanning electron microscopes, and many other applications. In the past 10 years, several LaB_6 hollow cathodes have been developed at JPL for use in high power Hall thrusters[14-16]. The smallest version of this cathode has been operated in xenon from 5 A to 60 A continuously and used extensively in the 6-kW H6 Hall thruster at JPL, U. Michigan, and AFRL. The mid-sized version has operated at 5 to 200 A, and extensively life tested at discharge currents of 25 A for use in the Hermes 12.5 kW Hall thruster. The largest version is intended for use in very high power Hall thrusters such as the X3, and has been tested at discharge currents of 300 A in the laboratory and up to 250 A in the X3 Hall thruster [ref]. The designs all utilize a LaB_6 insert in a hollow tube made of molybdenum, with a tungsten orifice plate and an Al_2O_3 insulated, tantalum sheathed heater. The cathodes use graphite sleeves to interface the LaB_6 with the supporting structure, and also have a graphite keeper. In this paper, the characteristics of the large 2-cm insert diameter LaB_6 hollow cathode will be described, and improvements to reduce the orifice plate temperature and facilitate gas injection in the near cathode plume to damp instabilities that produce energetic ions at high discharge currents will be discussed. In addition, plasma parameters internal to the insert and energetic ion production reduction by the two different gas injection schemes are described.

II. LaB_6 Characteristics

Lanthanum hexaboride was first developed as an electron emitter by Lafferty[17] in the 1950's and its characteristics extensively described in our previous publications. Lanthanum hexaboride[17] is a crystalline material made by press-sintering LaB_6 powder into rods or plates and then electron-discharge machining the material to the desired shape. Polycrystalline LaB_6 cathodes have a work function of about 2.67 eV depending on the surface stoichiometry[18], and will emit over 10 A/cm^2 at a temperature of 1650 ˚C. Since the bulk material is emitting, there is no chemistry involved in establishing the low work function surface and LaB_6 cathodes are insensitive to impurities and air exposures that would normally destroy a BaO dispenser cathode. In addition, the cathode life is determined primarily by the evaporation rate of the bulk LaB_6 material at typical operating temperatures[19-21]. The higher operating temperature of LaB_6 and the need to make contact with LaB_6 with compatible materials has perhaps unjustly limited their use in the US space program.

The major reason for using LaB_6 cathodes, as compared to conventional impregnated dispenser cathodes, is the incredible robustness, high current density and long life exhibited by LaB_6 electron emitters. Lanthanum hexaboride cathodes are routinely used in all noble gases from helium to xenon, reactive gases including hydrogen and oxygen, and various other materials including liquid metals such as bismuth. LaB_6 cathodes have even been successfully used in oxygen and nitrogen plasma discharges at emission current densities exceeding 20 A/cm^2, and vented to water vapor (from cooling lines breaking) and air during operation without damaging the cathode. Lanthanum hexaboride cathodes are ideally suited for high current operation in hollow cathodes because they operate at sufficiently high temperatures (>1600 ˚C) to radiate excessive heating from the high density insert plasma generated during high current operation. LaB_6 hollow cathodes have been successfully operated at over 800 A. The space heritage of LaB_6 cathodes in Russian and US spacecraft is considerable, and the university and industrial experience in dealing with the higher operating temperatures and materials compatibility issues is extensive.

III. Experimental Configuration

The LaB_6 hollow cathodes described here for space applications are configured in a geometry similar to conventional space dispenser hollow cathodes[30], which basically consists of an active thermionic insert placed inside a structural cathode tube that is wrapped by a heater, heat shields, and keeper electrode. LaB_6 cathodes of this design have been fabricated with insert outside diameters of 0.63-cm to 2-cm and cathode lengths from the exit orifice to the base flange from 6 cm to 15 cm for applications in different thrusters that require various cathode sizes[6, 8]. The small LaB_6 hollow cathode with the 0.63-cm-outer-dia. insert was previously described in detail[5] and operated at discharge currents of 10 to 60 A. Likewise, the 1.5-cm diameter insert cathode was designed for operation from 10 to 100 A and tested at discharge currents of up to 200 A[8,31]. The cathode that is the subject of this paper is the largest of this family of cathodes with a 2-cm outer-dia. insert, a 3.5-cm outer-dia. keeper, and a 15-cm cathode length. This cathode was originally designed to run from 25 to 350 A, and has been tested at steady state discharge currents from 10 A to 300 A.

As mentioned above, the material in contact with the LaB_6 insert is typically made of graphite because it has a similar coefficient of thermal expansion[26,35] as LaB_6 and inhibits boron diffusion in to support materials at high temperature. The cathode tube is normally made from a refractory metal such as molybdenum or Mo-Re, with graphite sleeves used to interface with and contact the LaB_6 insert. A schematic representation of the molybdenum-tube configuration for the 2-cm-dia. LaB_6 hollow cathode is shown in Fig. 1. The keeper electrode used to start the discharge is also fabricated from graphite. The LaB_6 emitter is configured as a cylindrical insert and is placed inside the hollow molybdenum tube. The LaB_6 insert is held in place with a tungsten spring and refractory metal or graphite "pusher tube" placed inside the cathode tube. The cathode tube is sufficiently long and thin to minimize conduction of heat from the insert to the base plate. The insert in this larger cathode case has an outer diameter of about 2 cm, an inside diameter of 1.3 cm and a length of 5 cm, which provides 20 cm^2 of emission area exposed to the plasma inside the hollow cathode insert. If the emission is uniform along the length of the insert, at an insert temperature of 1700 ˚C this cathode can emit 20 A/cm^2 and therefore potentially produce total current of about 400 A. A photograph of the cathode as configured to use in the Hall thruster is shown in Fig. 2.

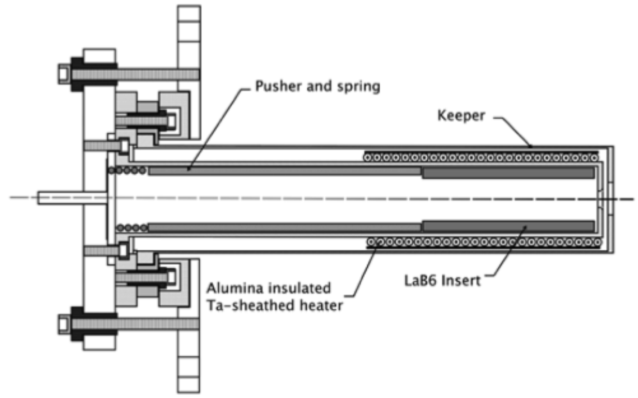

Fig. 1. Schematic drawing of the 2-cm-dia. LaB_6 hollow cathode.

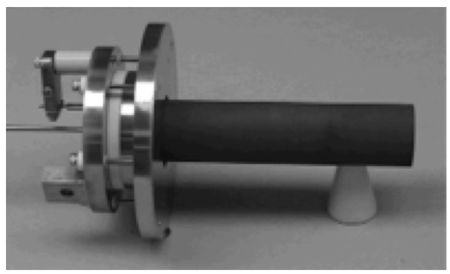

Fig. 2. The laboratory-model 2-cm-dia. LaB_6 hollow cathode.

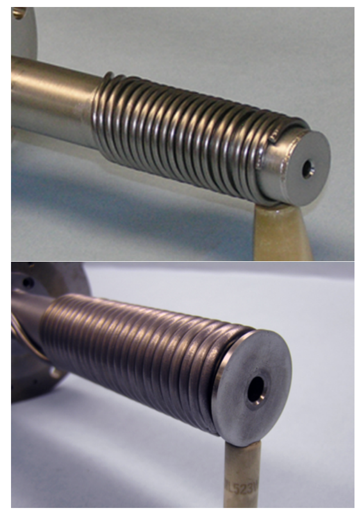

Fig. 3. Original cathode orifice plate (top) and newer version (bottom) with large diameter orifice plate.

A major issue with the original configuration of this cathode was excessive orifice plate temperatures at discharge currents over 150 A. This problem was mitigated by increasing the diameter of the cathode plate orifice diameter to 0.64 cm, and by increasing the outer diameter of the cathode orifice plate to be the same as the heater and heat shield, which significantly increases the radiation area. Figure 3 shows the original design (top) and the 2nd generation version (bottom). The only issue in fabrication of this geometry was that the heater has to be wound and installed on the cathode tube before the tungsten orifice plate is e-beam welded onto the cathode tube.

The temperature of the orifice plate as a function of discharge current for the two cathode orifice plate configurations is shown in Fig. 4. The original design produced orifice plate temperature over 2200 ˚C at 250 A, while the larger diameter orifice plate design maintained the orifice plate well below 2000 ˚C at about 225 A. Since the orifice plate temperature was the major factor limiting the discharge current, this improved design permitted reliable operation of the cathode at up to 250 A of discharge current. However, this is still relatively high and likely insufficient for operation at the planned 350 A for the highest power levels of the X3 thruster. An even larger diameter orifice plate was installed on the most recent version of the cathode to provide this capability, which is discussed below.

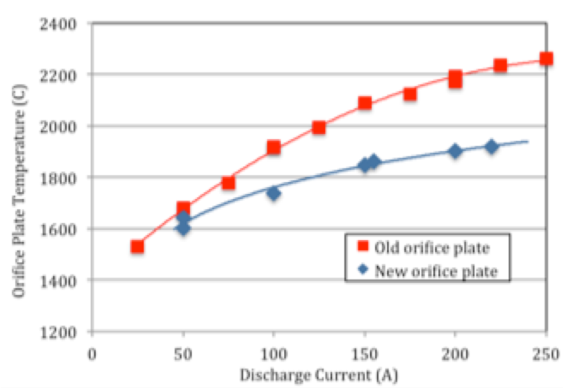

Fig. 4. Orifice plate temperature versus discharge current for two outside diameters of the cathode orifice plate.

The cathode was operated in one of the JPL cathode test facilities[8,35] at discharge currents up to 300 A. The cathode installed in the test facility is shown in Fig. 5a. The facility has a 1-m-dia. by 2.2-m-long vacuum system with 1250 l/sec xenon pumping speed from two cryo-pumps. A solenoid coil is positioned around the keeper electrode to provide an adjustable axial magnetic field at the cathode exit. The anode consists of a water-cooled tapered cylinder of relatively large area to handle the high-power discharge. This test configuration produces discharge voltages in the 15 to 30 V range, depending on the current and gas flow rate. As seen in Fig.5, the RPA and one of the probes are positioned in the gap between the cathode and anode to investigate the energetic ion production mechanisms and impact on cathode life.

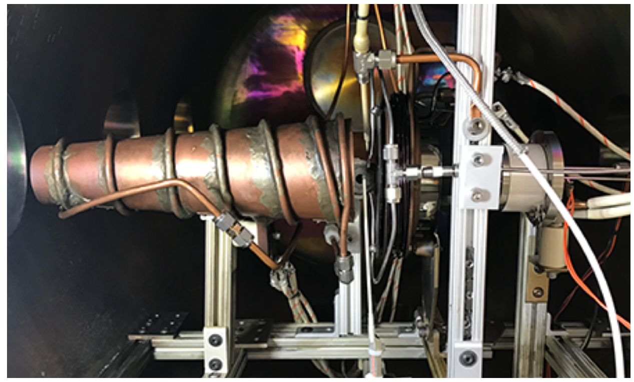

Fig. 5a. High power test facility setup with gas injectors.

The assembly includes two cathode-plume gas injectors[12] shown in Fig. 5b that are used to reduce the generation of energetic ions in the cathode plume and reduce the discharge voltage at higher discharge voltage. The cathode and gas injector assembly used in the tests in the X3 Hall thruster is shown in Fig. 6. An additional gas injection path between the cathode tube and keeper tube was also introduced into this updated cathode design. This path injects neutral gas directly into the cathode plume through the keeper orifice without significantly affecting the pressure inside the cathode insert region. The flow through the cathode and the internal pressure is optimized to produce a relatively flat density profile and plasma contact with the entire length of the insert for uniform thermionic emission, while the gas injectors reduce the energetic ions produced outside the cathode insert region.

Temperature measurements of the cathode orifice plate are made using a DFP 2000 Disappearing Filament Optical Pyrometer calibrated by a tungsten filament reference in the vacuum system. A comparison of the measured temperature of the filament to that derived from simple radiation theory was used to obtain a calibration curve to correct the readings of the orifice plate temperature through the vacuum system window.

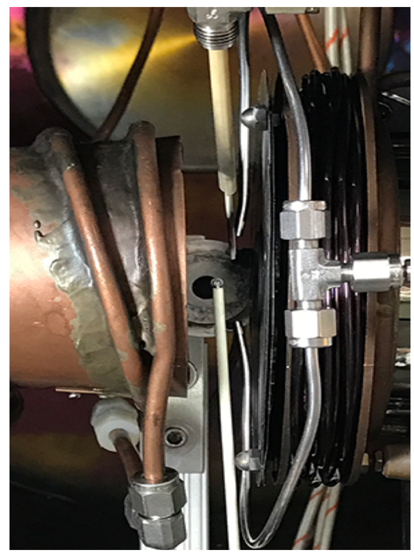

Fig. 5b. Close-up photo of RPA, external gas injectors and two probes used for cathode-plume studies.

IV. LaB_6 Cathode Discharge Performance

After installation in the test facility, the system was pumped down into the 10^{-6} Torr range and the cathode heater turned on for 15 minutes. The cathode discharge was then started by initiating the xenon gas flow through the cathode, applying 150 V to the keeper electrode and turning on the anode power supply. The keeper current was regulated to 2 A, and the keeper voltage fell to a value typically in the 5 to 10 V range depending on the gas flow rate. Once the anode discharge current exceeded 10 A, the heater and keeper power supplies were turned off and the keeper allowed to float. The cathode was normally run at 25 A for a minute or two until the discharge voltage stabilized, and then it could be turned up to full current in less than a minute. The discharge current versus voltage characteristics for this cathode are largely unchanged from the previously published version [ref].

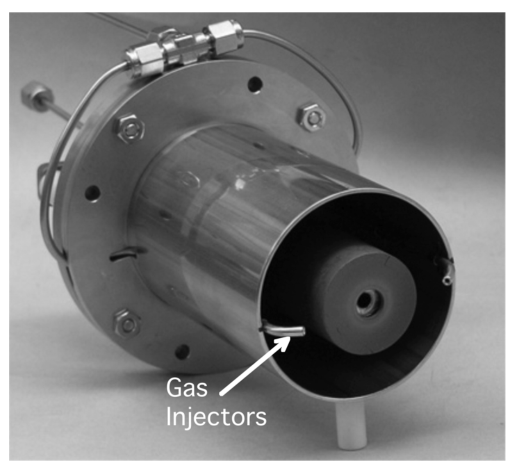

Fig. 6. Lanthanum hexaboride hollow cathode assembly with cathode-plume gas injectors.

Figure 7 shows the discharge voltage versus discharge current for the 2-cm-dia. cathode measured at 16 sccm xenon flow thought the cathode for currents of 25 to 200 A. The effect of the “external” gas injection and the "internal" injection (between the cathode and keeper tubes) is also shown. The thermal design of this cathode has been improved such that at discharge currents below 50 A the discharge voltage was observed to be relatively flat with current. Operating at currents below 10 A required keeper currents in excess of 2 A to keep the cathode hot. The gas injectors reduce the discharge voltage slightly, and interestingly the internal injector was more efficient at reducing the discharge voltage at higher discharge currents.

In order to operate the cathode at discharge currents above 250 A in this facility, it was necessary to use the external gas injectors shown in Fig. 5b to reduce the discharge voltage below the 30 V maximum of the discharge power supply. Figure 8 shows the discharge voltage versus current for the cases where external gas injection was used. Discharge currents of up to 300 A were achieved at discharge voltages below 26 V when 20 sccm of external gas injection was used. Gas injection was also required to reduce the generation of energetic ions in the near-cathode plume at high discharge currents[8,10]. This is discussed in the next section.

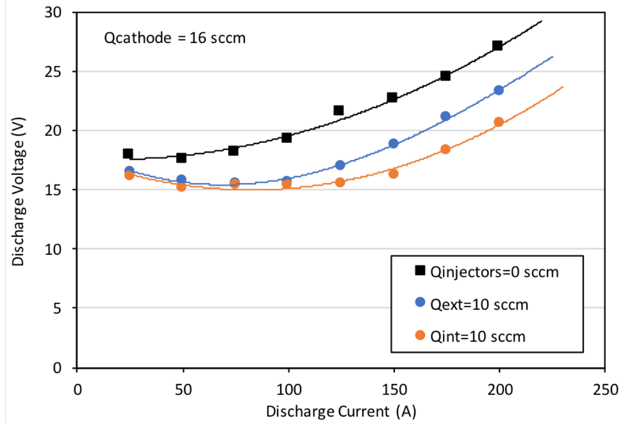

Fig. 7. Discharge voltage versus current at 16 sccm xenon showing the effect of flow through the two injector systems.

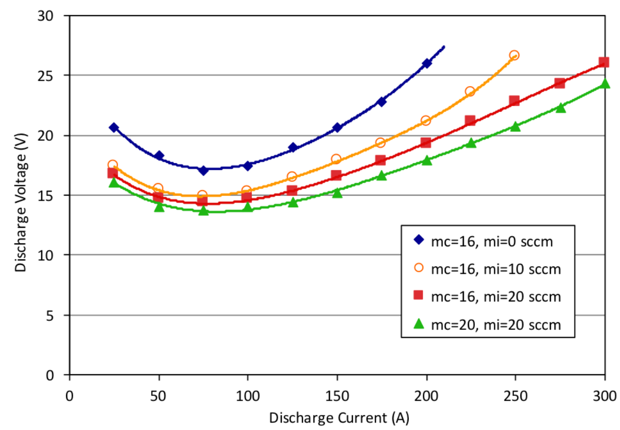

Fig. 8. Discharge voltage versus current showing the effect of external gas injection. Discharge currents of up to 300 A were achieved with sufficient external injection.

V. Discussion

A. Orifice Plate Heating

On an earlier version of this cathode [ref], the cathode orifice plate was enlarged from the same size as the cathode tube outer diameter to 1.14" OD (Fig. 3) to increase the radiation area and reduce the temperature. Nevertheless, the orifice plate was observed to operate at temperatures of about 2000 ˚C at discharge currents approaching 250 A. This is attributed to the high cathode orifice heat fluxes associated with high discharge current operation, and the effective heat shielding of the enclosed keeper assembly. A thermal model of the 1.14" OD orifice plate cathode was developed and benchmarked against the results shown in Fig. 3. This model was then used to size a larger orifice plate to reduce the operating temperature at higher discharge currents.

Figure 9 shows the hollow cathode tube and heater assembly with the 1.26" dia. orifice plate and the tantalum heat shield over the sheathed heater. Figure 10 shows the orifice plate temperature as a function of discharge current for the three cathode orifice plate diameters tested to date. The original 1.14" dia. cathode orifice plate temperature data is shown in blue symbols, and a second identical cathode built several years later had the same behavior shown by the green symbols. The thermal model was benchmarked at 100 A discharge current, and the orange triangles show that the thermal model does well at higher current following the data.

The orifice plate temperature measured with the 1.26" dia. orifice plate is shown by the red open circles. The larger orifice plate reduced the temperature by nearly 100˚C at every current. The model predictions are given by the closed red squares, which are slightly lower than the measured temperatures. This is likely due to a different emissivity assumed for the graphite keeper, which

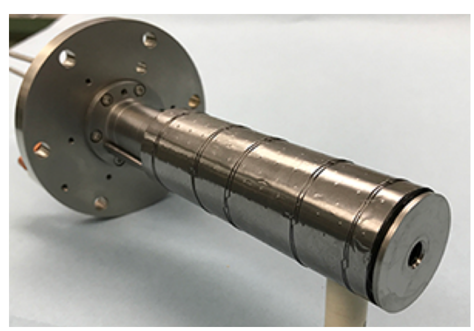

Fig. 9. LaB_6 hollow cathode with the 1.26" dia. orifice plate.

would effectively heat shield the cathode orifice plate if lower than expected. Nevertheless, the larger diameter orifice plate reduced the measured temperature to about 1965˚C at 300 A, and the data trend suggests that temperatures on the order of 2000˚C would be obtained at up to 350 A. This is an acceptable orifice plate temperature because it produces an insignificant evaporation rate for the pure tungsten orifice plate material.

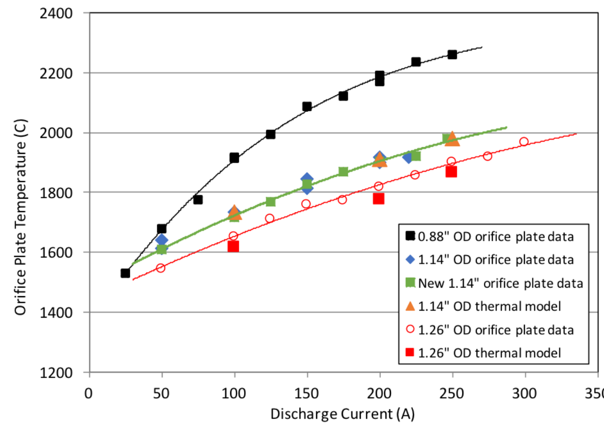

Fig. 10. Orifice plate temperature for three orifice plate diameters at discharge currents of up to 300 A.

B. Internal Plasma Density Profiles

Of critical importance in hollow cathodes is the axial plasma density profile in the insert region [ref]. This is because the insert temperature profile depends on the plasma contact area, and more uniform axial densities result in more uniform insert temperatures and evaporation rates. Also, space charge can limit the thermionic emission current if the plasma density becomes too low toward the upstream end of the insert, limiting the effective emission area and how much current the insert can emit into the plasma.

Figure 11 shows the plasma density profiles as a function of position inside the insert region for various discharge currents up to 200 A at 16 sccm cathode flow conditions. The electron temperature in the insert region is about 2.5±0.5 eV and the plasma potential inside the insert varied from about 14V down 8V as the discharge current increased. As observed previously in hollow cathodes [ref], the plasma density shifts downstream toward the orifice plate at higher discharge currents. The plasma contact area with the 5-cm long insert in the high current cathode may be limited at currents above 100 A. This density profile is likely affected by the insert temperature profile, and a flatter profile will emit more current upstream and flatten the density profile. To this end, a set of heat shields were installed inside the cathode just upstream of the insert to minimize radiation losses from the insert to the cathode tube and back flange. Additional plasma density measurements and insert temperature measures are planning in the future to determine the effectiveness of this approach.

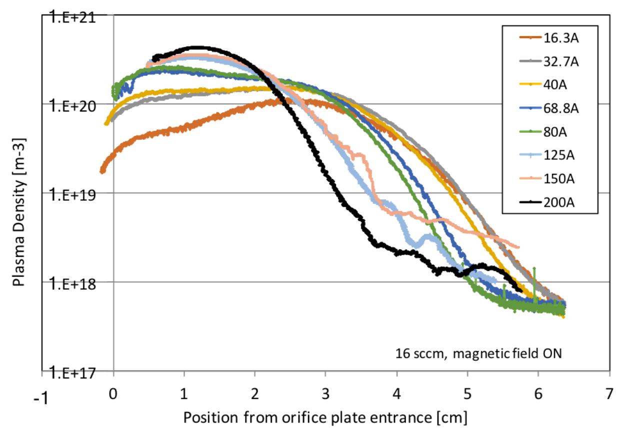

Fig. 11. Internal plasma density profiles at various currents for 16 sccm cathode flow conditions.

C. Energetic Ion Production

The production of high-energy ions in the near-cathode plume of hollow cathodes increases significantly with discharge current. These ions sputter-erode the cathode keeper and cathode orifice plate, which strongly impacts the cathode life. The energetic ions are produced by either plasma potential fluctuations from ionization instabilities in the thruster plume [10], or by turbulent ion acoustic waves or drift waves [ref. Jorns] also in the near cathode plume. The four-grid RPA was used to measure the ion energy distribution [10,13] at discharge currents up to 250 A. The ion energy distribution is proportional to the first derivative of the current-voltage characteristic obtained from the RPA, and is related to the ion voltage distribution function f(V) by Eqn. 11:

$$\frac{dI}{dV} = -\frac{q^2 e^2 n_i A_c}{M} f(V) \tag{1}$$

where q is the charge-state of the ion, e is the electron charge, n_i is the ion density, A_c is the probe collection area, and M is the mass of the xenon ion[48]. Due to the noise in the collected current signal, current-voltage data from the RPA is fit to a 17[th]-order polynomial and the derivative of that polynomial fit used to determine the ion energy distribution.

Figure 12 shows the ion energy distribution for three discharge currents with 10 sccm flowing through the cathode and 5 sccm flowing through the external injector. At the higher current (for this flow), ions with energies in the range of 30 to 60 eV are observed. Increasing the internal gas through the cathode to 16 sccm or the external injector flow to 10 sccm readily reduces the energy of these ions below 20 eV.

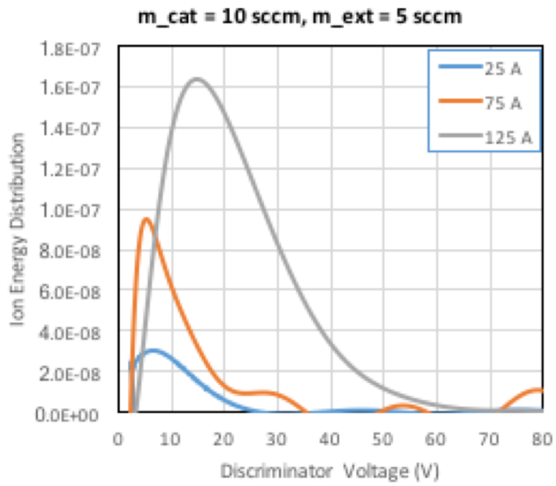

Fig. 12. Ion energy distribution at three discharge currents for 10 sccm flow through the cathode and 5 sccm through the external injector. 30 to 60 V energetic ions are observed at higher currents.

The "internal" injector that flows gas between the cathode and keeper tubes and out the keeper orifice is nearly as effective as the external injector in eliminating the energetic ion production. Figure. 13 shows the ion energy distribution measured at 225 A for the case of 16 sccm flowing through the cathode and 15 sccm flowing either through the external or internal injectors. The ion energy is similar in both cases, with the external injectors reducing the ion energy slightly more. This is likely due to the fact that the gas flowing between the cathode and keeper tubes is heated by the hot cathode tube, and the lower gas density that results in the plume due to this hotter gas flow is less efficient in damping the instabilities that cause the energetic ions. The addition of 10-20% more internal flow causes the ion energy content to be essentially the same.

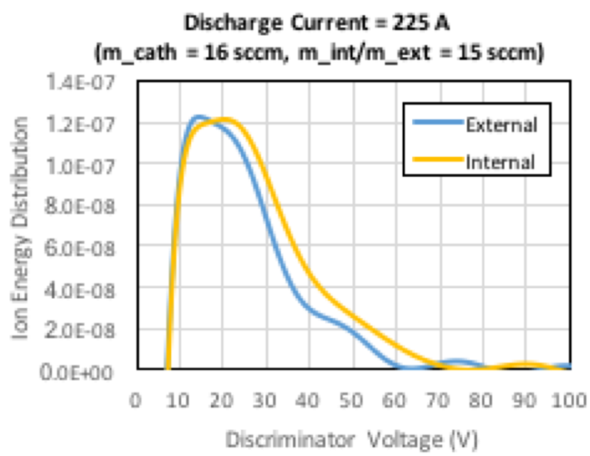

Fig. 13. Ion energy distribution at 225 A of discharge currents for 16 sccm flow through the cathode and 15 sccm through the external injector or the internal injector.

It should be noted that Chu [ref] previously showed ion energies well in excess of 100 eV at these high discharge current conditions. Those measurements used the same RPA and experimental setup as used here, but the very high ion energies reported were actually due to a hardware problem in the data acquisition system. This was corrected in the present measurements, and the maximum ion energy observed (without using the gas injectors) did not exceed 100 eV over the discharge conditions tested.

VI. Conclusion

Lanthanum hexaboride hollow cathodes have been developed at JPL that cover the discharge current range from 5 to over 300 A. The small LaB_6 cathode version has been operated at up to 40 A of discharge current in the H6 Hall thruster, and the middle size LaB_6 hollow cathode has run at over 31 A of discharge current in the HERMeS Hall thruster. The 2.0-cm-dia.-insert version of this LaB_6 hollow cathode configuration has been upgraded and now can provide discharge currents ranging from 10 to 300 A. This cathode has been successfully operated in the X3 Hall thruster at discharge currents of up to 250 A. The cathode design features a robust molybdenum cathode tube, a tungsten cathode orifice plate and a graphite keeper. The tantalum sheathed heater technology that uses Al_2O_3-powder insulation has proven to be very reliable in heating these higher temperature cathodes to ignition. The hollow cathode assembly includes two cathode-plume gas injectors to reduce the energetic ion production in the near-cathode region that can limit the life of the keeper electrode at the very high discharge currents that this cathode has demonstrated. The cathodes have calculated lifetimes in the 10 to 20 khrs range depending on their operating conditions, and experiments have shown the path to even higher currents and longer lifetimes if required by future missions.

Acknowledgments

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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